Center for
By-Products
Utilization

EFFECTS OF TEMPERATURE AND FLY ASH ON BEHAVIOR OF HIGH-PERFORMANCE CONCRETE

By Tarun R. Naik, Rudolph N. Kraus, and Shiw S. Singh

Report No. CBU-1999-05
REP-359

For Publication and Presentation at the International Conference on "Infrastructure Regeneration and Rehabilitation, Improving the Quality of Life Through Better Construction: A Vision for the Next Millennium", June 28 - July 2, 1999, Sheffield, U.K.

Department of Civil Engineering and Mechanics
College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN -MILWAUKEE

EFFECTS OF TEMPERATURE AND FLY ASH ON BEHAVIOR OF HIGH-PERFORMANCE CONCRETE

Tarun R. Naik[1], Rudolph N. Kraus[2], and Shiw S. Singh[3]

ABSTRACT

Based on investigations conducted at the UWM Center for By-products Utilization, two different HPC mixtures were proportioned to have the 28-day compressive strength of 85 MPa. The first mixture (Mix 15P) contained 9% Class C fly ash and 14% silica fume and the other mixture (Mix 15E) contained 25% Class C fly ash, 17% Class F fly ash, and 6% silica fume by weight of cementitious materials. Two types of curing methods, standard moist-curing and Variable Temperature Curing Environment (VTCE), were used. For the VTCE, temperature was varied from 29 ± 3°C for 12 hours each day to 41 ± 3°C for the remaining 12 hours each day, to simulate hot weather curing. Tests were conducted to study the influence of temperature on compressive strength, resistance to chloride-ion penetration, air and water permeabilities, and sulfate attack. At 28 days, compressive strengths of the mixtures were 99 MPa and 100 MPa for Mix 15P, and 84 MPa and 88 MPa for Mix 15E for the moist-cured and VTCE-cured specimens, respectively. Both HPC mixtures show excellent performance with respect to compressive strength, resistance to chloride-ion penetration, sulfate attack, and alkali-silica reaction.

Keywords: high performance concrete, sulfate attack, curing temperature, fly ash, silica fume.

---

(1) Director, UWM Center for By-Products Utilization, University of Wisconsin Milwaukee, Milwaukee, Wisconsin 53201, USA

(2) Assistant Director, UWM Center for By-Products Utilization, University of Wisconsin Milwaukee, Milwaukee, Wisconsin 53201, USA

(3) Formerly Post-Doctorate Fellow, UWM Center for By-Products Utilization, University of Wisconsin Milwaukee, Milwaukee, Wisconsin 53201, USA

INTRODUCTION

Conventionally, researchers have used strength properties of concrete as criteria for evaluating its performance. A concrete having high strength does not necessarily imply that it will have long-service life. Thus, it is now well recognized that concrete performance should be determined in terms of both strength and durability under anticipated environmental conditions. Various definitions exist for high-performance concrete (HPC). The ACI Committee on High-Performance Concrete (1) defines HPC as, "Concrete meeting special performance requirements which cannot always be achieved routinely using any conventional constituents and normal mixing, placing, and curing practices. These requirements may involve enhancements of the following: ease of placement without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, and life in severe environments." Thus, HPC should have both high-strength and high-durability properties pertinent to an application.

In the USA and elsewhere, concrete structures are deteriorating at a faster rate than expected. This is primarily due to the fact that structures are subjected to higher loads than intended and/or subjected to an aggressive chemical environment. Moreover, concretes used in those structures were generally proportioned based on water to cementitious materials ratio alone to meet specified strength requirements. Many of them did not contain either mineral admixtures or high-range water-reducing admixtures that are needed in production of durable concrete. HPC appears to be an excellent candidate for use in many structures such as tunnels, ocean piers, off shore platforms, pipes, structures for confinements of solids and liquid wastes containing hazardous materials, etc. whose designs require to have both high-strength and high-durability.

At high temperature, concrete microstructure is negatively affected. Poor microstructure is associated with generation of undesirable configuration of C-S-H crystals, reduced degree of hydration, and increased cracking at high temperature curing. Generally, the C-S-H crystals grow long and thin/narrow and occupy less space in the matrix at high temperatures, resulting in decreased density of the microstructure. The reduced degree of hydration at elevated temperature occurs as a result of rapid water loss due to evaporation, leaving unhydrated cement particles within the concrete matrix. The increased microcracking is the result of high thermal stresses that are generated due to the induced temperature gradients. Thus, homogeneity and density of concrete microstructure are adversely affected due to the aforementioned factors. Consequently, long-term strength and durability-related properties are negatively affected for concrete subjected to curing at high temperatures.

HPC is a relatively new class of advanced cement-based material. There is a lack of data on design and performance of HPC, especially under controlled hot weather conditions. Therefore, this work was directed toward investigating the effects of curing temperature on behavior of HPC.

PREVIOUS STUDIES

It is now well established that a very dense homogeneous concrete microstructure, especially in the interface region between hydrated paste and aggregate, is required in order to produce HPC (2-15). This is generally achieved through the use of low water to cementitious materials ratio (0.20-0.30) with the help of superplasticizers that can produce slumps ranging from 75 to 125 mm (3 to 5 in.). Additional densification and homogeneity of the interfacial region are achieved through the inclusion of mineral admixtures such as fly ash, silica fume, etc. These mineral admixtures are known to improve the concrete microstructure, due to both pore as well as grain refinements. In general, studies reported in recent publications (8, 9, 12, 14, 15), have indicated that concretes made with good quality aggregates and other constituent materials at low water to cementitious materials ratio (around 0.25 ± 0.05) exhibit high strength and low permeability. The permeability dictates the rate at which aggressive agents such CO_2 gas and/or liquids carrying deleterious substances (deicers, acid rain, sea water, sulfate rich water, etc.), penetrate into concrete, causing various types of expansive reactions. The stresses generated due to such reactions often cause damage to concrete. Therefore, the measure of permeability is directly related to the durability of concrete to improve its quality or performance.

High-strength concrete (HSC) up to 55 MPa can be produced using locally available materials and conventional concrete production technology at low water to cementitious materials ratio (2, 5, 6, 9, 10, 11). The required workability of such mixtures is obtained using high-range water-reducing admixtures, generally called superplazticizers. For HPC above 70 MPa (10,000 psi), special constituent materials, mixture proportioning, production technologies, etc. are needed in order to ensure long-service life. This may involve the use of special aggregates (small size, closely graded, high-strength), low heat of hydration cement, special admixtures, and special care in mixing, handling, and placing. Mehta and Aitcin (6) reported that for very high strength levels, particularly above 100 MPa, aggregate size should not exceed 10 to 12 mm. Naik and his co-workers (4, 8, 9, 10, 11) have developed HPC mixtures for strengths up to 100 MPa using coarse aggregates with size ranging between 12 and 20 mm.

Studies (17, 18, 19), have indicated that the use of Class F fly ash and silica fume improves concrete resistance to sulfate. Some studies (16, 17) reported that inclusion of Class C fly ash reduces ability of concrete to resist sulfate attack. However, Mehta (18, 20) indicated that irrespective of calcium content, it is the amount of reactive alumina content contributed by a fly ash that controls the presence of mineral highly vulnerable to sulfate attack. ACI Committees 201 and 318 offer recommendations to stem the effects of sulfate attack (21, 22).

The alkali hydroxides generated during cement hydration can react with amorphous silica containing aggregates, resulting in formation of expansive products. Generally, use of Class F fly ash and silica fume, either individually or combined in concrete, suppresses alkali-silica reactions. Numerous investigations (23, 24, 25) have reported influence of temperature on concrete performance due to exposure to high temperatures.

Sarkar (26) reported complementary and synergistic effects of mineral admixtures such as fly ash, slag, and silica fume on concrete microstructure. Silica fume is most reactive and thus it contributes to early-age densification of the cementitious matrix including the transition zone. Therefore, silica fume has the most dominant effect on the early-age strength among other cementitious materials used. Progressive hydration of slag or fly ash contributes to the later-age strength. Further densification of the concrete microstructure occurs due to pore filling effects of slag or fly ash. Therefore, in order to derive favorable microstructure of HPC, it is desirable to use binary or ternary combination of mineral admixtures to obtain the best results.

EXPERIMENTAL PROGRAM

Materials

An ASTM C 150 Type 1 cement was used in this investigation. A Class C fly ash and a Class F fly ash conforming to ASTM C 618 requirements and a silica fume conforming to ASTM C 1240 were also used. The fine aggregate consisted of natural sand. The coarse aggregates consisted of 19 mm (¾ in. maximum size) crushed limestone. Both aggregates met the ASTM C 33 requirements. A commercially available superplasticizer and a retarder were also used. The superplasticizer was used to obtain the desired consistency of concrete at low water to cementitious materials ratio. The retarder was used to control the rate of hydration reaction to avoid damaging effects of accelerated hydration due to evolution of heat of hydration and to permit placement and finishing of the concrete mixtures.

Mixture Proportion

Based on previous experience with the use of fly ash in HPC (3,4), two basic mixtures were proportioned to have strength of 85 MPa at the age of 28 days. The first mixture contained 9% Class C fly ash and 14% silica fume and was designated as Mix 15 P. This mixture was expected to have high-strength and durability-related properties. The second mixture contained 25% Class C and 17% Class F fly ash and 6% silica fume and was designated as Mix 15 E. The 15 E mixture was referred to as an economical mixture because it was proportioned with a smaller amount of silica fume and with a much larger amount of fly ash to reduce the production cost of the concrete. Both the concrete mixtures were produced at slumps ranging between 50 and 200 mm in laboratory conditions. The details of mixture proportions are presented in Tables 1 and 2. Four concrete batches for each mix were required for specimen casting and testing. Each batch produced was approximately 0.15 m^3 of concrete.

Preparation of Test Specimens

Measured weights of coarse and fine aggregates were placed in a 0.16 m^3 mixing capacity revolving concrete mixing drum and allowed to mix for two minutes. The cement and fly ash were then added to the mixer and allowed to dry mix with the aggregates for two more minutes. At the end of the dry mixing, one half of the required amount of superplasticizer and all of the retarder were mixed in a bucket with the required amount of water for each batch. The water and admixture combination were then added to the mixer. For Mix 12.5 P, the required amount of silica fume slurry was added at the same time as the water/admixture combination. The wet concrete was then allowed to mix for three minutes and rest for two minutes. During the two minute rest period, wet concrete that adhered to the surface of the drum was manually scraped off. At the end of the two minute rest period, the remaining amount of superplasticizer was added to the mixture and the resulting concrete was mixed again for three minutes. Soon after mixing, tests were conducted and properties of fresh concrete such as slump (ASTM C143), air content (ASTM C 231), and temperature (ASTM C1064) were recorded. Ambient air temperature was also recorded. Cylindrical specimens (100 mm x 200 mm) were cast for compressive strength and resistance to chloride-ion penetration measurements. Slab specimens (100 mm thick x 300 mm x 300 mm) were cast for air and water permeability measurements. Prism specimens (100 mm x 75 mm x 400 mm) were cast for sulfate resistance evaluations. All specimens were cast in accordance with ASTM C 192.

Curing of Specimens

Two types of curing systems were used. The first curing type was the standard moist curing in a laboratory at 23°C (73°F) and 100% relative humidity. The second type of curing involved the use of a specially designed system in order to maintain Variable Temperature Curing Environment (VTCE) with temperature varying from 29 ± 3°C for 12 hours each day to 41 ± 3°C for the remaining 12 hours each day, to simulate hot weather curing. All specimens were wrapped in plastic before placing them in the VTCE. The relative humidity of the VTCE chamber was found to vary between 35 and 85%.

Testing of Specimens

Compressive strength tests were conducted in accordance with ASTM C 39. Chloride-ion penetration resistance was measured in accordance with ASTM C 1202. Air and water permeabilities were measured using the Figg Method (27,28). Prism specimens, after initial length measurements, were immersed in a 10% sulfate solution for evaluation of sulfate resistance. Each specimen was tested for length change (ASTM C 157), density (ASTM E 12), and longitudinal frequency (ASTM C 215). The sulfate solution in each container was replaced with a new solution after each measurement.

RESULTS AND DISCUSSIONS

Compressive Strength

Compressive strength data are shown in Table 3 and Fig. 1. As expected concrete strength increased with age. In general, both mixtures showed strength in excess of 46 MPa (6700 psi) at the early age of three days. At three days, the maximum compressive strength (66 MPa) was achieved by Mix 15 P for VTCE-cured specimens, while the minimum compressive strength (46 MPa) was attained by moist-cured Mix

15 E. The same relative values were also noticed at the age of seven days but all mixtures showed strengths in excess of 60 MPa (8,700 psi) for both curing environments. Generally, all VTCE-cured specimens exhibited higher strengths than corresponding moist-cured specimens at the ages up to 28 days. All mixtures attained strengths in excess of 84 MPa at 28 days. Moist-cured specimens exhibited 99 MPa (14,330 psi) for Mix 15P, and 84 MPa (12,230 psi) for Mix 15 E at the 28-day age. Whereas corresponding mixtures cured in the VTCE attained 100 MPa (14,530 psi) and 88 MPa (12,800 psi) at the age of 28 days.

Moist-cured specimens of Mix 15P at 56 days attained a strength higher than specified, exhibiting strength of 105 MPa (15,160 psi). Under the same condition, Mix 15E achieved a compressive strength of 93 MPa (13,430 psi). VTCE-cured specimens attained strengths of 101 MPa (14,590 psi) for Mix 15P and 96 MPa (13,860 psi) for Mix 15E at the age of 56 days. At 91 days, except for moist-cured Mix 15 E, compressive strengths of both HPC mixtures were not significantly different than those observed at 56 days for both curing environments. This is due to the fact that these mixtures, generated higher heat of hydration than normal strength concrete due to their relatively high cement content. Consequently, they achieved higher rate of hydration reaction, resulting in accelerated setting and hardening. Moreover, the hydration rate of VTCE-cured specimens was further accelerated due to the temperature effects. As a result, the major strength gain occurred up to the age of 28 days. The rate of strength gain decreased substantially beyond 28 days and it became insignificant after 56 days of curing for both curing environments.

Resistance to Chloride-Ion Penetration

Concrete resistance to chloride-ion penetration was evaluated in accordance with ASTM C 1202. The chloride-ion penetration resistance data are shown in Tables 4 and 5 and Fig. 2. Generally, Mix 15P attained higher resistance to chloride-ion penetration than did Mix 15E in both curing environments. This was partly due to higher silica fume content of Mix 15P compared to Mix 15 E. The silica fume is more reactive than Class C or Class F fly ash. Thus, Mix 15 P containing higher amount of silica fume produced better microstructure than the other HPC mixture, especially at early ages. However, at later ages, concrete microstructure was heavily dependent upon pozzolanic reactions of the fly ashes. Moreover, densification of the microstructure results from the pore filling effect of the fly ashes. Therefore, concrete microstructure was positively affected due to the blends of silica fume and fly ashes. Also, fly ash helped control rate of hydration reaction, thus reduced the damaging effects of rate of reactions of cement-rich mixtures. As anticipated, concrete resistance to chloride-ion penetration improved with age (Tables 4 and 5 and Fig. 2).

The effect of temperature was significant on concrete ability to resist chloride-ion penetration. At the age of about one month, moist-cured specimens of Mix 15P showed an average reading of 240 coulombs compared to an average reading of 105 coulombs for specimens cured in the VTCE. Whereas, moist-cured specimens of Mix 15E exhibited an average reading of 1040 coulombs compared to 385 columns for specimens cured in the VTCE. A similar trend was also observed at later ages of 56 and 91 days (Fig. 2). At the age of one month, both moist-cured HPC mixtures were rated to have very high resistance to chloride-ion penetration ("very low" chloride-ion penetration in accordance with ASTM C 1202) in the

VTCE. However, Mix 15E attained high resistance to chloride-ion penetration and Mix 15P attained very high resistance to chloride-ion penetration in the moist-curing environment at the age of about one month.

Both HPC mixtures attained excellent performance at and beyond the age of 56 days for both curing environments.

Air and Water Permeabilities

Each HPC mixture was evaluated for air and water permeabilities in accordance with the Figg Method (27, 28). The test data are reported elsewhere (9). The Figg Method permeability results did not exhibit any particular trend with respect to air and water permeabilities of the HPC mixtures tested in this investigation. This was attributed to microcracking of the concrete possibly created due to the drilling of the test holes. This test procedure appears to affect the results considerably when used to test high-strength concrete because of a high degree of brittleness of such concretes. Other researchers (23) have also reported this problem. Consequently, it was decided to evaluate the performance of the HPC mixtures based on the chloride-ion penetration resistance only. For concrete with compressive strength up to 50 MPa, the Figg Method has been used successfully to measure the air and water permeabilities (5).

Sulfate Resistance

The effects of sulfate attack on concrete specimens are shown in Fig. 3 through Fig. 8. The change in density as a function age due to immersion in a 10% sulfate solution is shown in Fig. 3 for moist cured specimens and Fig. 4 for VTCE-cured specimens. The change in density was small in both of the curing environments for Mix 15P. The density change for Mix 15E also followed the same general trend as that observed for Mix 15P (Fig. 4).

The length change data are depicted in Fig. 5 for Mix 15P and Fig. 6 for Mix 15E. Generally, the length change for both mixtures was found to be insignificant for both environments.

Generally, the dynamic modulus for both mixtures increased with age when exposed to sulfate ions (Fig. 7 and 8). The dynamic modulus values of VTCE-cured specimens were significantly higher compared to moist-cured specimens for either HPC mixture. This was primarily the result of higher maturity of VTCE-cured specimens relative to that for moist-cured specimens at a given age. The modulus values of the concrete mixtures increased with age due to their exposure to the sulfate solution. The improved performance occurred possibly due to the favorable curing in the sulfate solution.

CONCLUSIONS

Based on the experimental investigation completed in this study, the following main conclusions can be drawn.

1. Both HPC mixtures (Mix 15P and 15E) showed high rate of strength development up to 28 days. Beyond 28 days, the rate of strength development decreased significantly, and after 56 days of curing in either environment, the rate of strength gain became insignificant.
2. Generally, VTCE-cured specimens achieved higher rate of strength development compared to moist-cured specimens for all mixtures.
3. Both HPC mixtures exhibited high early-age strengths, exceeding 46 MPa at the age of three days in either curing environment. At 28 days, compressive strength varied between 84 and 99 MPa for moist-cured specimens and between 88 and 100 MPa for VTCE-cured specimens.
4. Mix 15P showed a strength of 104 MPa and Mix 15E attained 93 MPa under moist-curing environment at the age of 56 days. The corresponding VTCE-cured mixtures showed compressive strength of 101 MPa and 96 MPa at 56 days.
5. The resistance to chloride-ion penetration increased with increased amount of silica fume from 6% to 14% of total cementitious materials.
6. In general, concrete resistance to chloride-ion penetration increased with age, i.e., with increase in strength of concrete.
7. The use of the VTCE increased concrete resistance to chloride-ion penetration. This trend was also reported by Cabrera et al. (24). The temperature effect was dominant at the ages up to 56 days. Beyond 56 days, the effect of temperature was negligible. All concrete mixtures were rated to have a

very high resistance to chloride-ion penetration ("very low" chloride-ion penetration in accordance with ASTM C 1202 criteria) at the age of 56 days and beyond.

8. The air and water permeabilities data recorded by using the Figg method were inconsistent. Therefore, the Figg method was found to be inadequate for evaluating permeability of HPC mixtures.
9. The influence of curing type on sulfate resistance of the HPC mixtures was insignificant. Both HPC mixtures attained very high resistance to sulfate attack as no appreciable change in length and density values were observed due to their exposure to the sulfate solution (10% sulfate ion). In fact, performance of these mixtures improved due to their curing in the sulfate-enriched liquid. Both mixtures exhibited increases dynamic modulus values with age during their immersion in the sulfate solution.

REFERENCES

1. *Planning Committee for the Nationally-Coordinated Program on High-Performance Concrete and Steel*, *High-Performance Construction Materials and Systems*: An Essential Program for America and Its Infrastructure, Technical Report No. Report 93-5011, April 1993
2. Mehta, P.K. Concrete Technology at the Crossroads - Problems and Opportunities, *Proceeding of the V. Mohan Malhotra Symposium on Concrete Technology - Past, Present, and Future, P.K. Menta, Ed., ACI SP-144*, 1994, pp. 1-30
3. Naik, T.R., and Ramme, B. High Early Strength Fly Ash Concrete for Precast/Prestressed Products, *PCI Journal*, Vol. 35, No. 6, Nov./Dec., 1990, pp. 72-78
4. Naik, T.R., and Patel, V., and Brand, L. Performance of High-Strength Concrete Incorporating Mineral Admixtures, *Presented and Pre-print published at ACI National Spring Convention*, Washington, D.C., 1992
5. Naik, T.R., Singh, S.S., and Mohammad M. Properties of High Performance Concrete Incorporating Large Amounts of High-Lime Fly Ash, *International Journal of Construction and Building Materials,* U.K., Vol. 9, No., 6, 1995, pp. 195-204
6. Aitcin, P.C., and Neville, A. High-Performance Concrete Demystified, *ACI Concrete International*, January 1993, pp. 21-26
7. Mehta, P.K., and Aitcin, P.C. Principles Underlying Production of High-Performance Concrete, *Cement, Concrete, and Aggregates*, ASTM, Vol. 12, No. 2, Winter, 1990, pp. 70-78
8. Beffel, J. Curing Temperature Effects on High-Performance Concrete Properties, University of Wisconsin - Milwaukee, *M.S. Thesis*, 1995
9. Olson, Jr., W.A. Temperature Effects on the Permeability of High-Performance Concrete, University of Wisconsin-Milwaukee, *M.S. Thesis*, 1994
10. Patel, V. Full-Scale Beam Tests for Shear Strength of High-Strength Concrete, University of Wisconsin-Milwaukee, *M.S. Thesis*, 1992
11. Brand, L. Shear Strength of Reinforced Concrete Beams for High-Strength Concrete, University of Wisconsin-Milwaukee, *M.S. Thesis*, 1992
12. Aitcin, P.C., Sarkar, S.L., Regourd, M., and Hornain, H. Microstructure of a Two-Year-Old Very High Strength (100 MPa) Field Concrete, *Proceedings, Symposium on High-Strength Concrete*, Tapir

Publishers, Trondheim, Norway, 1987, pp. 99-109

13. De Larrand, F., Ithurralde, G., Acker, P., and Chavel, D. High-Performance Concrete for a Nuclear Containment, *Proceedings of the Second International Symposium on High-Strength Concrete, SP-121*, ACI, 1990, pp. 5549-5576
14. Gjorv, O.E. High Strength Concrete, *Advances in Concrete Technology*, V.M. Malhotra, Ed., CANMET, Ottawa, Canada, 1994, pp. 19-82
15. Aitcin, P.C. Durable Concrete - Current Practice and Future Needs, P.K. Mehta, Ed., SP-144, ACI, 1994, pp. 85-104
16. Naik, T.R., and Singh, S.S. Use of High-Calcium Fly Ash in Cement-Based Construction Materials, *Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, Milwaukee, WI, 1995, Supplementary Proceedings, V.M. Malhotra, Ed., pp 1-44
17. Malhotra, V.M. Fly Ash, Slag, Silica Fume, and Rice Husk in Concrete: A Review, *ACI Concrete International*, Vol. 15, No.4, April 1993, pp.23-28
18. Mehta, P.K. Pozzolanic and Cementitious By-Products in Concrete - Another Look, *Proceedings of the Third CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Trondheim, Norway, V.M. Malhotra, Ed., ACI SP-114 1989, pp.1-43
19. Tikalsky, P.J., and Carrasquillo, R.L. Influence of Fly Ash on Sulfate Resistance of Concrete, *ACI Materials Journal*, Vol. 89, No. 1, January - February 1992, pp. 69-75
20. Mehta, P.K. Effects of Fly Ash Composition on Sulfate Resistance of Cement, *ACI Materials Journal,* Vol. 83, No.6, 1986, pp. 94-100
21. ACI Committee 201: Guide for Durable Concrete, *American Concrete Institute*, Detroit, Michigan
22. ACI Committee 318: Building Code Requirements for Reinforced Concrete *(ACI 318-95), American Concrete Institute*, Detroit, Michigan
23. Owen, P.L. Effect of Temperature Rise and Fall on the Strength and Permeability of Concrete Made with and without Fly Ash, Temperature Effects on Concrete, ASTM STP 858, T.R. Naik., Ed., *American Society for Testing Materials*, Philadelphia, 1985, pp. 134-149
24. Cabrera, J.G., Dodd, T.A.H., and Nwaubani, S.O. The Effect of Curing Temperature on the Chloride Diffusion of Superplasticised Cement and Fly Ash Cement Pastes, *ACI SP 139-4*, 1993, pp. 61-76
25. Naik, T.R., and Singh, S.S. "Curing Temperature Effects on Properties of Class F Fly Ash Concrete, *a paper presented and preprint published at the ACI Spring Conference*, Tarpon Springs, FL, March 1994, 36 pages
26. Sarkar, S.L. Role of Silica Fume, Slag, and Fly Ash in the Development of High-Performance Concrete Microstructure, *Proceeding of the ACI International Conference, Singapore, ACI SP-149*, V.M. Malhotra, Ed., 1994, pp. 449-460
27. Figg, J.W. Methods of measuring the air and water permeability of concrete, *Magazine of Concrete Research*, Vol. 25, No. 85, December 1973, pp. 213-219
28. Cather, R., Figg, J.W., Marsden, A.F., and O'Brien, T.P. Improvements to the Figg Method for Determining the Air Permeability of Concrete, *Magazine of Concrete Research*, Vol. 36, No. 129, December 1984, pp. 241-245

Table 1: Mixture Proportions for HPC Mixture 15P

MIXTURE NUMBER*	15P1	15P2	15P3	15P4
Specified 28-Day Design Strength, MPa	85	85	85	85
Cement, kg/m^3	498	471	473	476
Class C Fly Ash, kg/m^3	63	59	59	59
Class F Fly Ash, kg/m^3	0	0	0	0
Silica Fume, kg/m^3	93	88	88	89
Water, kg/m^3	141	134	136	137
Sand (SSD), kg/m^3	729	692	691	695
19 mm Aggregates (SSD), kg/m^3	994	943	942	949
Superplasticizer, L/m^3	10.6	10.1	10.1	10.1
Retarder, L/m^3	1.8	1.7	1.7	1.7
Slump, mm	100	88	51	64
Water to Cementitious Materials Ratio	0.22	0.22	0.22	0.22
Air Content, %	2.0	2.8	2.8	2.5
Air Temperature, °C	23.3	23.3	23.3	23.3
Concrete Temperature, °C	21.7	21.7	22.8	25
Concrete Density, kg/m^3	2461	2429	2414	2418

* 15P1, 15P2, 15P3, and 15P4 represent four different batches of Mix 15P

Table 2: Mixture Proportions for HPC Mixture 15E

MIXTURE NUMBER*	15E1	15E2	15E3	15E4
Specified 28-Day Design Strength, MPa	85	85	85	85
Cement, kg/m^3	348	371	342	365
Class C Fly Ash, kg/m^3	161	172	158	169
Class F Fly Ash, kg/m^3	107	115	106	113
Silica Fume, kg/m^3	40	43	40	43
Water, kg/m^3	158	177	162	174
Sand (SSD), kg/m^3	562	600	552	589
19 mm Aggregates (SSD), kg/m^3	857	914	840	896
Superplasticizer, L/m^3	5.4	5.6	5.6	5.7
Retarder, L/m^3	1.6	1.7	1.5	1.7
Slump, mm	114	152	165	203
Water to Cementitious Materials Ratio	0.24	0.25	0.25	0.25
Air Content, %	2.4	2.1	1.9	1.9
Air Temperature, °C	22.8	23.3	23.9	22.8
Concrete Temperature, °C	24.0	24.4	21.7	21.7
Concrete Density, kg/m^3	2358	2384	2363	2360

* 15E1, 15E2, 15E3, and 15E4 represent four different batches of Mix 15E.

Table 3: Compressive Strength Test Results

Test Age,	Moist Room Lab Cured, MPa *		Variable Temperature Cured, MPa *	
Days	15P Mixture	15E Mixture	15P Mixture	15E Mixture
3	64.1	46.2	65.6	47.0
7	73.3	60.7	85.7	70.3
28	98.8	84.3	100.2	88.3

56	104.5	92.6	100.6	95.6
91	103.4	99.1	103.1	98.0

* Average of three readings

Table 4: Chloride Ion Penetration Test Results for Specimens Subjected to Moist Curing *

Mixture No.	Age (Days)	Average Charge Passed, Coulombs **
15P1	31	240
15P1	56	180
15P1	91	150
15E2	31	1040
15E2	56	415
15E2	91	405

Table 5: Chloride-Ion Penetration Test Results Subjected to Variable Temperature Curing Environment *

Mixture No.	**Age (days)**	**Average Charge Passed, Coulombs ****
15P1	32	105
15P1	56	65
15P1	91	200
15E2	34	385

15E2	56	125
15E2	91	355

* Chloride-ion penetration resistance was determined in accordance with ASTM C1202

** Average of three readings

FIGURES 1F-8F ARE ON APPLE DISK FOR REP-311